U.S. BUREAU OF MINES TECHNOLOGY APPLICABLE TO DISASTER RESPONSE, URBAN SEARCH AND RESCUE

J. G. Kovac, H. Dobroski, and D. Litton
U.S. Bureau of Mines
P.O. Box 18070
Pittsburgh, PA 15236

ABSTRACT

Since 1910, the U.S. Bureau of Mines (USBM) has investigated practical ways of dealing with the consequences of major fires and explosions in underground mines. The results of this research have had a significant positive impact on the mining community by enhancing mine workers' chances of surviving an underground mine disaster.

Today, the Bureau continues to conduct research in mine disaster mitigation. Much of this work has direct application to search and rescue situations, such as: emergency evacuation through smoke-filled or otherwise unbreathable atmospheres, locating and rescuing survivors from rubble piles, and fire fighting in confined spaces.

Three USBM research areas are discussed:

(1) Life Support -- This effort is directed toward research into and development of closed-circuit breathing apparatus for use in hazardous environments which are likely to be encountered in the aftermath of a mine disaster.

(2) Trapped Miner Location -- A mine disaster may result in the entrapment of miners whose normal escape routes are cut-off. This research activity resulted in the development of transportable seismic technology that can be used to locate trapped miners.

(3) Mine Fire Diagnostics -- This research involves developing practical techniques for remotely monitoring how the atmosphere inside a mine changes during a fire, in order to estimate the spread and severity of an underground fire. This information is critical in deciding how best to fight a mine fire, or whether it is safe to mount a rescue and recovery mission.

INTRODUCTION

At the turn of the century, mine disasters were a commonplace event. It was not unusual for hundreds of lives to be lost in a single instant when an explosion erupted in a mine. The carnage reached such a level that congress established the USBM with the intent to improve technology and give the mining industry the means to provide a safer work place.

In the years that have passed since then, the mining industry assisted, by the USBM, the Mine Safety and Health Administration (MSHA), and other Federal and State agencies, has greatly improved its safety record. The overall accident rates for mining have greatly decline, and fires and explosions no longer account for the majority of work related deaths. Although the frequency of explosions has diminished to nearly zero, they still occur. It is against these occurrences that the USBM performs research into post-disaster technologies.

LIFE SUPPORT

In a mine fire or explosion, the mine

atmosphere can quickly become unbreathable. Along with smoke, there will be carbon monoxide and the possibility of toxic byproducts from other burning materials. Depending on ventilation conditions, the atmosphere may also become deficient in oxygen.

To protect escaping miners, Federal mining law (Title 30 CFR, part 75.1714) requires that every person that enters an underground coal mine be supplied with a Self-Contained, Self-Rescuer (SCSR). An SCSR is an emergency breathing apparatus designed specifically for the purpose of mine escape. The law also calls for these SCSR's to meet certain minimum requirements in order to be approved for use. Among these requirements it is specified that the SCSR be able to provide at least a 60-minute supply of oxygen (O_2). The National Institute for Occupational Safety and Health (NIOSH) and MSHA act jointly in providing certification for SCSR's.

Description of the Basic Technology

Part of the USBM effort in life support is to lead the drive for improved SCSR technology. By working cooperatively with manufacturers, the Bureau was able in 1989 to introduce second-generation SCSR's to the mining industry. Second-generation SCSR's are both smaller and lighter than the first-generation SCSR's that they are replacing, but are still able to meet the same performance criteria.

The main advantage derived from this improvement comes in deployment. The previous SCSR's were too large to carry and had to be stored in the mine near the locations at which people regularly work. One disadvantage of this deployment scheme in an emergency is the delay in escaping while an individual travels to a storage location to look for an SCSR. Since second generation SCSR's are person-wearable, miners can begin their escape immediately.

All second generation 1-hr SCSR's approved for use at this writing employ mainly potassium superoxide (KO_2), a solid, as the oxygen source and as a carbon dioxide (CO_2) absorbent.

Figure 1 is an engineering drawing of a chemical oxygen SCSR. One significant feature is that SCSR's deliver a breathable atmosphere through a mouthpiece, rather than a mask or face piece. A mouthpiece combined with nose clips provide a high degree of user protection without the penalty of custom fitting.

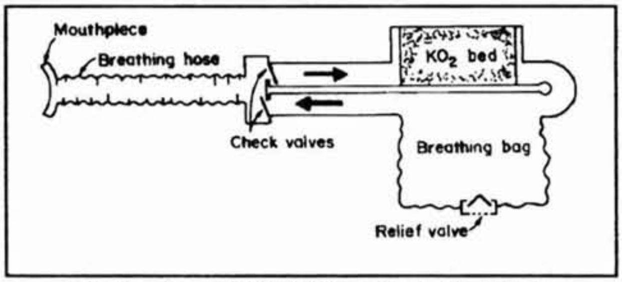

Figure 1.--Typical Chemical O_2 SCSR

Three of the four manufacturers who held current certifications for their original SCSR's have designed and gained approval for second-generation SCSR's. All three of these are chemical oxygen units. These devices are smaller and lighter than the ones they replaced. The sizes and weights of these devices, compared to their first-generation counterparts, are given in Table 1.

Although SCSR's were specifically designed for mine escape, they can also be used for escape or evacuation in other hazardous situations, such as a chemical plant fire or tunnel fire. Compared to other closed-circuit breathing apparatus intended for emergency use, SCSR's have a number of advantages: small size and weight, low maintenance, long service life, easy and quick donning, no custom fitting, and relatively low deployment costs.

Table 1.--Size and Weight Comparison of First- and Second-Generation SCSR's

		Weight (kg)	Size (L)
	Draeger		
1st	OXY-SR 60B	3.8	8.2
2nd	OXY K plus	2.8	5.7
	MSA		
1st	60-min SCSR	4.0	7.3
2nd	Portal-Pack	2.4	3.7
	CSE		
1st	AU9-A1	4.4	6.3
2nd	SR-100	2.5	3.2

TRAPPED MINER LOCATION

In some cases escape may be impossible due to injuries or damage to the mine. The only alternative may be to seek out the safest place possible, wait, and hope for rescue.

In such a situation, time is of the essence. The toxic gases from a fire or explosion will often eventually migrate throughout the entire mine. Experience has shown that unless rescue is accomplished in a matter of hours, the trapped miners will likely perish. Therefore, the key to successful rescue is to verify that some miners have survived, and to determine their location. With such knowledge, rescue teams can focus their efforts more efficiently, and the likelihood of successful rescue is enhanced.

In 1970, the National Academy of Engineers recommended that a seismic system be built and tested as a means of detecting and locating trapped miners. Via contracts and in-house efforts, the Bureau developed such a system, which is shown in Figure 2. It consists of an array of geophones, arranged in subarrays, deployed on the surface of a mine, approximately above the disaster site. The location of the subarrays must be accurately sited by surveying. These geophones are designed to detect seismic signals generated by underground trapped miners. Signals detected by the subarrays are transmitted by wireline or radio link to a seismic instrumentation truck that contains computers, recorders, CRT displays, and other equipment. The truck can be driven or airlifted to disaster sites. For the seismic system to be effective, trapped miners must be trained to respond in a certain manner. This training can be provided by MSHA or company safety instructors. As an aid and reminder, a sticker that summarizes this training can be affixed to the inside of hardhats.

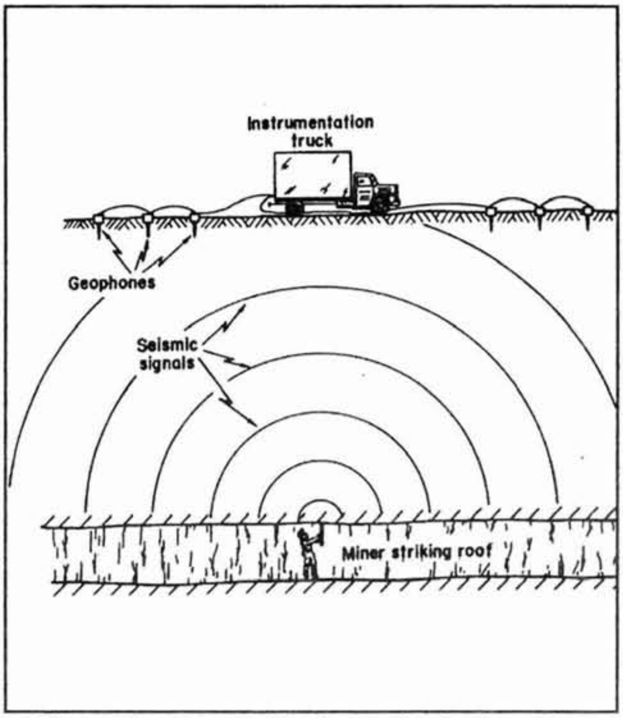

Figure 2.--Trapped miner seismic detection system.

Initially, the trapped miners should take action to improve their chances of survival. This includes keeping calm, gathering food and water, and possibly barricading to provide some degree of protection from toxic gas. Miners must also recognize that it may take hours (perhaps days) for the seismic system to arrive on the surface and be deployed. Therefore, it is important that they conserve strength, resources, and hope until then.

The first signal given when the seismic system is in place above them is three shots (explosions) detonated at the surface. These shots can easily be heard underground. At this signal, the trapped miner(s) must pound 10 times on the roof of the mine with a heavy object like a timber. This pounding is repeated every 15 minutes. This creates a pattern of seismic signals that propagate through the earth and reach the subarrays at the surface. The signals from each subarray are amplified and telemetered to the seismic truck, where they are filtered to reduce interferences, amplified, and recorded on analog magnetic tape. They are then band-pass filtered from 20-200 Hz and displayed on an oscillograph recorder.

The operator observes the record and decides whether or not the seismic signals are the result of underground pounding. The key, of course, is the series of 10 events repeated every 15 minutes. If such signals are observed, that portion of the magnetic tape is input into a computer which processes the data, taking into account the relative arrival times at the various subarrays. These data, along with information concerning the location of the subarrays, and the seismic velocity of the geologic strata, are used to calculate the location of the underground source. Under favorable conditions, the system can detect these seismic signals from a distance of about 600 m (2000 ft), with a location accuracy of about 30 m (100 ft). When the surface seismic team has ascertained the location, they detonate 5 explosive shots. This is the signal to the trapped miners that they have been detected and located. They should now stop pounding, and wait for rescue.

Seismic systems have application for detecting persons buried in landslides and collapsed buildings as a result of earthquakes or other natural disasters. However, a surface disaster is quite different from a mine disaster. In a mine disaster, the victims are trapped perhaps hundreds of meters from where geophones can be deployed. Also, there is no way of knowing exactly where the miners might be. In such a situation, detection is not enough. Accurate location is needed also. Both of these requirements can be met using seismic techniques, because the nature of the seismic path between the mine and the surface can be measured. In a surface disaster situation, the most important aspect is to verify whether or not there are survivors within a localized area. Rescuers generally know approximately where to look, because the distances involved are measured in tens of meters, not hundreds. Computer-based seismic location techniques, such as those used in the mine disaster situation, would not likely be successful in the surface case because of the chaotic and unconsolidated nature of the material between the victim and the geophones. These circumstances call for a different kind of seismic system, such as the one built by MSHA and successfully used in the Mexico City earthquake rescue efforts in 1985. This system, known as the "mini-seismic" system, was originally built for in-mine use, and can be carried by an advancing rescue team. It consists of three geophones, three preamplifiers, three filters, and a chart recorder. It is a detection system only, and has no computer-based location capability.

The human operator visually examines the magnitude of the three seismic signals, and decides which is the greater. The assumption is that the geophone registering the largest signal, is the one nearest the seismic source. By a series of measure and move operations, the system can zero in on the location of the seismic source.

MINE FIRE DIAGNOSTICS

Mine fire diagnostics are a set of techniques by which the mine air is sampled for combustion products to determine: 1) during the early stages of a fire, the status of the fire, in terms of its size and possibly the primary combustibles involved; or 2) after a mine, or a section has been sealed, whether or not a fire still exists, and if so, whether or not the fire is smoldering or flaming.

It is important to realize that in addition to diagnostics for fires, similar diagnostic procedures are also used to determine the explosibility of the mine atmosphere due to the accumulation of methane and other explosive gases. For either type of diagnostic, fire or explosibility, the basic techniques are the same. These techniques consist of obtaining gas samples from various mine locations, analyzing these samples, and interpreting the meaning of the resultant gas concentrations as they apply to either a fire or the explosibility of the gaseous mixture.

The differences in these techniques, as they apply to either of the two situations, are the result of the time-scales involved which dictate that different sampling, analysis, and interpretation procedures be used.

Situation No. 1
Diagnostics that are intended to determine fire status, fire location, and possibly the primary combustible involved must be rapid. In this instance, particularly with regard to fire-fighting strategy, time is critical. As much information as is possible regarding the fire must be obtained in a minimum amount of time. To implement a successful fire-fighting mission, several factors are critical:

1) Location
2) Accessibility
3) Fire Size and Growth
4) Combustible Type

Once the location of a fire is known, a determination of its accessibility must also be made. In very general terms, most fires are limited in their accessibility due to the smoke produced which reduces visibility. In particular, if the ventilation air velocity in the fire-affected entry is less than some critical level, reverse, stratified flow of smoke and other product gases can occur, thus limiting accessibility from the upstream side of the fire. This critical velocity is predictable from the expression

$$v_{crit}(m/s) \leq \left(\frac{gh}{10}\right)^{1/2}$$

where: $g = 9.8\ m/s^2$
h = entry height (m)

For instance, if the location of the fire is in an entry with a height of 1.5 m (5') and the air velocity in that entry is 0.50 m/s (100 fpm), then the fire-fighting team should expect to encounter smoke and reduced visibility from the upstream side of the fire, since the critical velocity for this entry is 1.2 m/s (240 fpm). This does not necessarily mean that some effort should be made to increase the air velocity because increasing the air velocity may enhance the flame spread of the fire in many cases, such as conveyor belt fires.

The decision to increase ventilation can more realistically be made if the fire size is known, or if the type of fire is known (i.e., flaming vs smoldering). This information can be obtained by measuring the levels of the gases, CO and CO_2, downstream of the fire. The level of CO_2 is an excellent indicator of the intensity of the fire. Some benchmark values of the CO_2 level can provide insight as to the stage of the flaming fire, and the ratio of CO to CO_2 can provide additional information on the type of fire. For a typical mine entry cross-section of 9.3 m^2 (100 ft^2) these levels are:

a) ppm $CO_2 < 150$ and $CO/CO_2 \geq 0.5$ indicates a smoldering fire in its early stages of development;

b) $150 < \text{ppm } CO_2 < 1500$ and $CO/CO_2 \leq 0.10$ indicates a localized flaming fire that is not spreading;

c) ppm $CO_2 > 1500$ and $CO/CO_2 \leq 0.10$ indicates a spreading fire that is fuel-lean;

d) ppm $CO_2 > 1500$ and $CO/CO_2 > 0.10$ indicates a spreading fire that is fuel-rich.

In addition, the absolute levels of CO provide information relevant to the toxicity of the atmosphere. For CO levels less than 250 ppm, no severe toxicity hazard is present from the CO. However, if combustibles other than liquid fuels, coal, or wood are involved some high level of toxicity may exist due to other gases. For instance, if chlorinated combustibles such as PVC or Neoprene conveyor belt are involved, elevated levels of HCl may be present; if nitrogen-based combustibles such as polyurethane foams are involved, elevated levels of HCN may be present.

It should also be mentioned that elevated levels of smoke, in excess of some critical level for visibility, often exist at very low levels of CO. In fact, the critical level of visibility for human escape is generally accepted to be 3.7 m (12 ft). This level of visibility occurs at a CO level of 20 ppm. In other words, severe reductions in visibility due to smoke can usually be expected, and often occur at relatively low levels of CO and other toxic gases.

It should be noted that the ventilation airflow serves to dilute the combustion product gases and smoke. As a result, when it is necessary to base some decision on the absolute level of either CO or CO_2, every effort should be made to make this measurement at a location downstream of the fire where the gas levels are due only to the ventilation airflow within the affected entry that is affected and not at some location where these gases may have been diluted by airflows from adjacent entries.

All of the above information applies to rescue operations, as well as fire-fighting. However, in assessing the feasibility of rescue operations, it is also necessary to obtain information about the level of O_2 present in order to assess the breathability of the atmosphere. Diagnostics for explosibility are also necessary.

These initial diagnostics need to be acquired rapidly and reliably because decisions need to be made quickly. As a result, the use of handheld gas analyzers for the primary gases CO, CO_2, CH_4, and O_2 is usually required. Such devices are generally available commercially.

Situation No. 2

Usually, the sealing of a mine, or section of a mine, is done as a last resort following unsuccessful local fire-fighting efforts. The intent of sealing is to allow the fire to self-extinguish as the supply of O_2 is gradually depleted. Unlike diagnostics for the early stages of a fire, time is not a critical factor in this situation. The Bureau of Mines has developed various gas ratios to assist in determining the status of fires in mines that have been sealed. Gas ratios are used instead of absolute concentrations because: 1) sealed areas enclose large volumes, so ratios are used in order to eliminate dilution effects; and 2) the typical time scale for attempting to recover a sealed mine is generally in the range of 2 to 12 months, but can be longer, and trending of gas ratios during this period is extremely beneficial.

The important thing to remember is that the bulk of necessary information for effective mine fire fighting can be obtained from the measurement of only four gasses: CO, CO_2, O_2, and CH_4. Only in fire emergencies involving gasses more toxic than CO, is it necessary to monitor these other gasses. These same techniques have direct application for attacking fires in any confined space, specifically, tunnels, and underground storage facilities.

CONCLUSION

Three USBM research areas were discussed: Life Support; Trapped Miner Location; and Mine Fire Diagnostics. The genesis of this research was to mitigate the consequences of mine disasters which are caused by underground fires or explosions. However, much of this work has direct application to search and rescue situations, such as: emergency evacuation through smoke-filled or otherwise unbreathable atmospheres, locating and rescuing survivors from rubble piles, and fire fighting in confined spaces.